Physics 105

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Chapter -30-
(Nuclear Physics and Radioactivity)

❖ Section (30.1): Structure and Properties of the Nucleus

- Nucleus refers to the central part of an atom, composed of *protons* and *neutrons*, and it carries most of the ***atom's mass***. The number of protons in the nucleus determines the element of the atom.
  - ➢ Proton: is the nucleus of the simplest atom, hydrogen.
    - ✓ The proton has a positive charge (**+1.60*10^{-19}**) and it has a mass (**m_p = 1.67262 *10^{-27} kg**)
  - ➢ Neutron: is subatomic particles located in the nucleus of an atom.
    - ✓ It is electrically neutral, meaning it carries no charge, and it has a mass (**m_n = 1.67493 * 10^{-27} kg**)

- Nuclides refer to ***different types*** of atomic nuclei.
  - ➢ Atomic number: is the number of protons in nucleus and is designated by the **symbol (Z)**.
  - ➢ Atomic mass number: is the total number of nucleons neutrons plus protons, is designated by the **symbol (A).**

- To identify a specific **nuclide**, only the values of A (mass number) and Z (atomic number) are needed. A commonly used special symbol represents this information in a specific format:

$$ {}_{Z}^{A}X $$

  - ➢ Isotopes: are nuclei that have *the same* number of *protons* but *different* numbers of *neutrons*
    - ✓ Like ${}_{6}^{12}C$, ${}_{6}^{11}C$, ${}_{6}^{13}C$
  - ➢ Isotones: are nuclides that have *the same* number of *neutrons*, but *different* number of *protons*
    - ✓ Like ${}_{18}^{40}B$, ${}_{6}^{13}C$
  - ➢ Isobars: are nuclides that have *the same mass number*
    - ✓ Like ${}_{18}^{40}Ar$, ${}_{19}^{40}K$

- For many elements, several ***different isotopes*** exist in nature.
  - ➢ Natural abundance: is the *percentage of a particular element* that consists of a particular isotope in nature.
    - ✓ Hydrogen has isotopes (99.99%) of natural hydrogen is ${}_{1}^{1}H$ a simple proton, as the nucleus; there are also ${}_{1}^{2}H$ called deuterium, and ${}_{1}^{3}H$ tritium, which besides the proton contain 1 or 2 neutrons. (The bare nucleus in each case is called the deuteron and triton)

- Due to ***wave-particle duality***, the exact size of the nucleus is somewhat indeterminate. Nuclei generally have a *spherical shape*, and the radius of a nucleus is given by:

$$ r = 1.2 * 10^{-15} * A^{\frac{1}{3}}\, m $$

- ✓ ***Example:*** Estimate the diameter of the smallest and largest naturally occurring nuclei:
  - **I.** ${}^{1}_{1}H$
  - **II.** ${}^{238}_{92}U$

- ✓ ***Solution:***
  - **I.** for ${}^{1}_{1}H$

    $r = 1.2 * 10^{-15} * A^{\frac{1}{3}}$

    $r = 1.2 * 10^{-15} * (1)^{\frac{1}{3}}$

    $r = 1.2 * 10^{-15}$ m

    so the diameter

    d = 2r

    $d = 2.4 * 10^{-15}$ m

  - **II.** for ${}^{238}_{92}U$

    $r = 1.2 * 10^{-15} * A^{\frac{1}{3}}$

    $r = 1.2 * 10^{-15} * (238)^{\frac{1}{3}}$

    $r = 7.436 * 10^{-15}$

    $d = 14.873 * 10^{-15}$

- ✓ ***Example:*** Approximately what is the ***value of A*** for a nucleus whose radius is $3.7 * 10^{-15}$ m?
- ✓ ***Solution:***

  $r = 1.2 * 10^{-15} * A^{\frac{1}{3}}$

  $3.7 * 10^{-15} = 1.2 * 10^{-15} * A^{\frac{1}{3}}$

  $A = 29.31 \approx 29$

- **Nuclear density** is about 10^{15} times greater than the density of normal matter.
  - ➢ While the density of *normal matter* ranges between $\mathbf{10^{3}}$ **and** $\mathbf{10^{4}}$, nuclear density falls within the range of 10^{18} to 10^{19}
  - ➢ The masses of nuclei are measured in ***atomic mass*** units (u).

$$\mathbf{1\ u = 1.6605 \times 10^{-27}\ kg = 931.5\ MeV/c^{2}}$$

TABLE 30–1
Rest Masses in Kilograms, Unified Atomic Mass Units, and MeV/c^2

Object	Mass		
	kg	u	MeV/c^2
Electron	9.1094×10^{-31}	0.00054858	0.51100
Proton	1.67262×10^{-27}	1.007276	938.27
${}^{1}_{1}$H atom	1.67353×10^{-27}	1.007825	938.78
Neutron	1.67493×10^{-27}	1.008665	939.57

❖ Section (30.3): Radioactivity

- Radioactivity: is the spontaneous emission of particles or radiation from the *unstable nucleus* of an atom as it undergoes decay to become more stable. This process occurs naturally in some isotopes, known as radioactive isotopes or radionuclides, and can also be ***induced artificially.***

- **There are three main types of *radioactive decay*:**

1. Alpha Decay (α-decay): In this type of decay, the nucleus emits an alpha particle, which consists of *two protons and two neutrons* (essentially a helium-4 nucleus). This results in a reduction of the atomic number by 2 and the mass number by 4 which could barely penetrate a piece of paper.

2. Beta Decay (β-decay): Beta decay occurs when a neutron in the ***nucleus transforms*** into a proton, emitting a beta particle (an electron or positron) and an antineutrino or neutrino. This process increases or decreases the atomic number by 1 without changing the mass number which could penetrate 3 mm of aluminum.

3. Gamma Decay (γ-decay): Gamma decay involves the release of energy in the form of **gamma rays** (high-energy photons) from a nucleus that has excess energy. Unlike alpha or beta decay, gamma decay ***does not*** *change the atomic or mass numbers* but **brings** the nucleus to a lower energy state which could penetrate several centimeters of lead

- We now know that **alpha rays** are helium nuclei, **beta rays** are electrons, and **gamma rays** are electromagnetic radiation.

❖ Section (30.8): Half -life and Rate of Decay

- Nuclear decay: is a random process the decay of any nucleus is *not influenced* by the decay of any other.
- Therefore, the number of decays in a short time interval is **proportional** to the number of nuclei present and to the time:

$$\Delta N = -\lambda N \Delta t$$

  - ✓ Where λ is a constant characteristic of that particular nuclide, called the *decay constant*

- This equation can be solved, using calculus, for N as a function of time:

$$N = N_\circ e^{-\lambda t}$$

  - ✓ N = *remaining* number of radioactive nuclei at time t
  - ✓ $N_\circ$ = *initial* number of radioactive nuclei at time $t_\circ = 0$
  - ✓ λ = decay constant

➢ The half-life: is the time it takes for *half the nuclei* in a given sample to decay. It is related to the decay constant:

$$T_{\frac{1}{2}} = \frac{In\ 2}{\lambda} = \frac{0.693}{\lambda}$$

  - ✓ Large λ ⟶ small $T_{\frac{1}{2}}$ ⟶ fast decay
  - ✓ Small λ ⟶ large $T_{\frac{1}{2}}$ ⟶ slow decay

✓ ***Example:***

I . What is the decay constant of $^{238}_{92}U$ whose half-life is $4.5*10^9$ yr?

II . The decay constant of a given nucleus is $3.2*10^{-5}$ s^{-1} .What is its half-life?

✓ ***Solution:***

I . For the decay constant of $^{238}_{92}U$:

$$T_{\frac{1}{2}} = \frac{In\ 2}{\lambda} = \frac{0.693}{\lambda}$$

$$4.5 * 10^9 = \frac{0.693}{\lambda}$$

$$\lambda = 1.54 * 10^{-10} \text{ yr}^{-1}$$

II . To calculate half-life

$$T_{\frac{1}{2}} = \frac{In\ 2}{\lambda} = \frac{0.693}{\lambda}$$

$$T_{\frac{1}{2}} = \frac{0.693}{3.2*10^{-5}} = 21656.25 \text{ s}$$

- Activity: It is the number of *decays per second*, or *decay rate(R),* represents the magnitude of the decay process.

$$A = \frac{|\Delta N|}{|\Delta t|} = A_{\circ} e^{-\lambda t} = \lambda N$$

✓ A = activity at time t

✓ $A_{\circ}$ = initial activity t = 0

- The unit of activity is the number of disintegrations per second, often measured in curies, Ci

1Ci = $3.70*10^{10}$ disintegrations per second

- The SI unit for source activity is the Becquerel (Bq):

1 Bq = 1 disintegration/s

➢ ***Mean life:*** is *average life time* of all the radioactive nuclei of a given radioactive element.

$$\tau = \frac{1}{\lambda} = \frac{T_{\frac{1}{2}}}{In2}$$

❖ Section (30.9): Calculations Involving Decay Rates and Half-life

✓ ***Example:*** The isotope ${}^{14}_{6}C$ has a half-life of 5730yr. If a sample contains $1.00*10^{22}$ carbon-14 nuclei ,What is the activity of the sample ?

✓ ***Solution:***

$T_{\frac{1}{2}} = \frac{0.693}{\lambda}$

$\lambda = \frac{0.693}{T_{\frac{1}{2}}} = \frac{0.693}{(5730yr)\left(3.156*10^{7}\frac{s}{yr}\right)}$

$\lambda = 3.83*10^{-12}\ s^{-1}$

$$A = \frac{|\Delta N|}{|\Delta t|} = \lambda N$$

$A = (3.83*10^{-12})\ (1*10^{22})$

$A = 3.83*10^{10}$ Bq

✓ ***Example:*** The activity of a sample drops by a factor of 6.0 in 9.4 minutes. What is its half-life?

✓ ***Solution:***

$A = A_{\circ}e^{-\lambda t}$

$\frac{\cancel{A_{\circ}}}{6} = \cancel{A_{\circ}}e^{-\lambda(9.4\ \text{min})}$

$\ln\left(\frac{1}{6}\right) = -\lambda(9.4 * 60)$

$-\ln 6 = -\frac{\ln 2}{T_{\frac{1}{2}}}(564)$

$T_{\frac{1}{2}} = \frac{(564)\ln 2}{\ln 6}$

$T_{\frac{1}{2}} = 218.18$ s

✓ ***Example:*** A laboratory has 1.49 µg of pure ${}^{13}_{7}N$, which has a half-life of 10 min

I. How many nuclei are present initially?

II. What is the rate of decay (activity) initially?

III. What is the activity after 1h?

IV. After approximately how long will the activity drop to less than one pre second ($=1s^{-1}$)?

✓ ***Solution:***

I. The atomic mass is 13.0, so 13.0 g will contain $6.02*10^{23}$ nuclei (Avogadro's number). We have only $1.49*10^{-6}$g, so the number of nuclei N_0 that we have initially is given by the ratio

13 grams of ${}^{13}_{7}N \longrightarrow$ 1 mole

$1.49 * 10^{-6}$ grams of ${}^{13}_{7}N \longrightarrow$ X mole

$X = \frac{1.49*10^{-6}\cancel{grams}*1mole}{13\cancel{grams}} = 1.146 * 10^{-7}$ mole

Number of nuclei of ${}^{13}_{7}N$ is $N = X*N_A$ ($N_A = 6.02 * 10^{23}$)

$N = 6.89 * 10^{16}$ nuclei

II. $A = A_{\circ}e^{-\lambda t}$

A = $\lambda N_0\ e^{-\lambda t}$

$A_0 = \lambda N_0$

$\lambda = \frac{In2}{T_{\frac{1}{2}}}$ ($T_{\frac{1}{2}}$ = 10*60 = 600 s)

$\lambda = 1.155*10^{-3}\ s^{-1}$

$A_0 = \lambda N_0$

$A_0 = 1.155*10^{-3} * 6.9*10^{16}$

$A_0 = 7.969*10^{13}$ Bq

III. $A = A_{\circ}e^{-\lambda t}$

A = $7.97*10^{13}\ e^{-\lambda t}$

$\lambda t = \frac{In2}{T_{\frac{1}{2}}} * t$

$\lambda t = \frac{In2}{10\ \cancel{min}} * 60\cancel{min}$

λt = 6 In2

A = $7.97*10^{13}\ e^{-6In2}$

A = $1.25 *10^{12}$ Bq

IV. $A = A_{\circ}e^{-\lambda t}$

$1 = 7.97*10^{13}\ e^{-\frac{In2}{600}t}$

$In(\frac{1}{7.97*10^{13}}) = \frac{-In2}{600}\ t$

$t = 2.7707*10^{4}$ s

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